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RECLAMATION OF ACID GENERATING TAILINGS USING FLOAT AND PHOSPHOGYPSUM AT COMINCO

FINAL REPORT
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L'objectif de reclamation pour les résidus produit par le concentrateur Sullivan de Cominco est l'établissement d'une communauté agricole capable de se supporter soir même et de satisfaire les règlements de reclamation de la Colombie Brittanique pour la propre productivité et gérance de la terre. La terre non dérangé autour des haldes à déchets a la meilleur capabilité physique comme terrain cultivable. Le développement des normes pour la productivite des terrains cultivables a été initier. La productivité et la qualité de la végétation poussée sur les résidus acides et traité avec phosphogypse/roche stérile, roches glaciaires morts-terrains/roche stérile, sol avec neutraliseur, chaux agricole, ont été determiné et comparé avec les normes locales.

La moyenne de la productivité du terrain cultivable, exprimé par kg/ha de fourrage produit, était 2559 kg/ha en 1986. La productivité relatif des résidus acides traité avec les techniques suivantes était:

1. 46 cm phosphogypse/roche stérile : 0.11
2. 50 cm roches glaciaires/roche stérile: 0.69
3. 90 cm sol sur résidus de silice oxydé: 0.62
4. résidus de silice oxydé traité avec : 0.89
   180 t/ha $CaCO_3$

Les concentrations élevées de fluorure dans le phosphogypse ont peut-être contribuées aux mauvais resultats avec le phosphogypse/roche stérile.

Seulement la végétation qui poussait dans les roches glaciaires morts-terrains et dans le sol était capable de se supporter soi-même. La production de fourrage augmentait avec un accroissement dans la profondeur de roche glaciaires ou de résidus au-dessus le sol. La capacité du sol pour l'humidité augmente avec la profondeur du milieu, un facteur très important pour soutenir l'accroissement des plantes pendant des conditions semi-aride. La contamination du sol mis directement sur les résidus de silice oxydé a reduit la profondeur des racines par 15%. La roche stérile a blockée effectivement la contamination du milieu ou les plantes poussaient. La profondeur des racines qui poussaient dans les résidus de silice oxydé n'a pas pu excéder la profondeur de la chaux.

La végétation qui poussait dans la phosphogypse/roche stérile avait accumuler le fluorure en concentration possiblement dangereuse aux animaux pâturants. La végétation qui poussait

dans la roche glaciaires/roche stérile, dans le sol qui couvrait le résidus de silice oxydé, et dans le résidus de silice oxydé avec la chaux avait la même qualité que le fourrage naturel.

Le phosphogypse ne peut pas être considéré acceptable pour la végétation des résidus acides jusqu' au moment que des méthods sont développées qui peuvent garantir que le fourrage soit d'une productivité acceptable et qu'il soit sauf pour consommation par les animaux; ou jusqu' au temps que d'autre méthodes acceptable pour la végétation et traitment de la terre sont développées.

SUMMARY

Establishment of a self-sustaining plant community capable of satisfying land use and productivity guidelines for reclamation in British Columbia is a reclamation objective for acid generating tailings at Cominco's Sullivan Concentrator. Undisturbed land adjacent tailing disposal sites has best physical capability for range land use. Development of productivity and quality standards for native range was initiated. Productivity and quality of vegetation grown on acid tailings revegetated using phosphogypsum/float rock, glacial till overburden/float rock, soil and a neutralizing reagent, agricultural grade hydrated lime, were determined and compared with preliminary local standards.

Productivity of native range, expressed as kg/ha of forage produced, averaged 2559 kg/ha in 1986. Relative productivity of revegetated acid tailings varied with reclamation technique as follows:

1.	46 cm phosphogypsum/float rock:	0.11
2.	50 cm glacial till overburden/float rock:	0.69
3.	90 cm soil on oxidized siliceous tailings:	0.62
4.	oxidized siliceous tailings treated with: 180 t/ha $CaCO_3$	0.89

Phytotoxic concentrations of flouride compounds may have contributed to poor vegetation establishment and growth on phosphogypsum.

Only vegetation growing on glacial till overburden and soil was self-sustaining. Forage production increased with an increase in depth of glacial till or soil covering tailings. Available moisture storage capacity increases with increasing depth of growth medium, an important factor for sustaining plant growth under local semi-arid climatic conditions. Contamination of soil placed directly on oxidized siliceous tailings reduced effective rooting depth by 15%. Float rock functioned effectively as a barrier preventing contamination of the growth medium. Rooting depth on limed oxidized siliceous tailings was limited to the depth of hydrated lime incorporation.

Vegetation growing on phosphogypsum/float rock accumulated fluoride-F in concentrations potentially toxic to grazing domestic and wild animals. Vegetation growing on glacial till

overburden/float rock, soil covering oxidized siliceous tailings and limed oxidized siliceous tailings was of similar quality as native range forage species.

Phosphogypsum should not be considered an acceptable material for covering and revegetating acid tailings until cultural techniques have been developed which guarantee acceptable productivity of forage species safe for consumption by domestic and wild animals or until acceptable land use and revegetation alternatives have been developed.

Reclamation of Acid Generating Tailings Using Float and Phosphogypsum at Cominco

1. Introduction

Alternative revegetation techniques for highly reactive sulphide tailings at Cominco's Sullivan Concentrator at Kimberley, B.C. were assessed. Industrial wastes, float rock and phosphogypsum, were compared with soil overburden and addition of neutralization reagents for improving conditions for vegetation establishment and growth. This assessment was a joint venture between Cominco Ltd. and CANMET, Division of Energy, Mines and Resources Canada. Cominco was responsible for planning and implementation of an intensive assessment program including maintenance of vegetation, sampling and analysis. CANMET agreed to share program costs. This report describes the background and objective of the project, the method of assessment and the results achieved during the 1986 growing season.

2. Background and Objective

The Sullivan Concentrator has been operational since 1923 producing lead and zinc concentrates along with over 60 million tonnes of acid generating sulphide tailings. The tailings were stored in large retaining ponds covering 365 hectares of land. With oxidation and weathering tailings rapidly developed an extremely acid reaction, salinity and adverse physical conditions which prevent revegetation (4). Addition of neutralization reagents or covering with suitable plant growth media are revegetation alternatives for these extremely phytotoxic mill wastes.

Float rock and phosphogypsum are industrial wastes available at the concentrator in sufficient quantity to cover the tailing ponds. Float is waste rock rejected by heavy media separation during the primary stage of ore concentration and assays approximately 0.2% Pb, 0.2% Zn and 5% Fe. Phosphogypsum is a solid by-product of phosphoric acid manufacture at Cominco's fertilizer operations near Kimberley. Ground phosphate rock, containing fluorapatite as a principal mineral constituent, and sulphuric acid are digested in a reaction vessel and then filtered. The filter cake, a mixture of components whose main constituent is $CaSO_4.nH_2O$, is generally referred to as phosphogypsum. Preliminary studies have demonstrated that float rock functions effectively preventing the capillary rise of contaminants from tailings into the growth medium and that herbaceous vegetation can sustain growth on phosphogyupsum (1,7). The studies also demonstrated that vegetation growing on

phosphogypsum accumulated elevated concentrations of fluoride often exceeding suggested safe levels for grazing animals (6,15).

Prior to 1985 phosphogypsum revegetation studies had not been conducted on a site having a limited depth of phosphogypsum placed over float rock. Information on the optimum depth of phosphogypsum and cultural practices required to sustain growth of herbaceous and woody species containing fluoride at levels safe for grazing animals had yet to be developed. A 0.67 hectare experimental site was constructed in October 1984 to accommodate these important investigations (3). An adequate depth of float rock to provide a stable working surface was spread over an oxidized iron tailing site having a shallow water table. The float rock was covered by a variable depth of phosphogypsum planned to range from 45 cm to 90 cm. Agricultural grade hydrated lime was applied at 20 t $CaCO_3$/ha to neutralize residual acid compounds and reduce fluoride availability to vegetation. Sixteen grass and legume species were seeded on the site in May 1985 to assess effect of phosphogypsum depth and forage specie on vegetation establishment, productivity and quality (9). Construction of the experimental site was a joint venture between Cominco Ltd. and CANMET (3).

Establishment of a self-sustaining plant community capable of satisfying land use and productivity guidelines for reclamation in British Columbia (1) and inhibiting acid generation and contamination of tailing effluent and seepage are important reclamation objectives for tailings at the Sullivan Concentrator. Undisturbed land adjacent the tailing ponds has best physical capability for native rangeland and sustains an open coniferous forest (11). The objective of this study was to assess the potential of the phosphogypsum/float rock reclamation technique to satisfy land use and productivity objectives. The impact of vegetation and cover materials on acid generation and contamination of tailing effluent and seepage will be assessed in future investigations.

3. Method of Assessment

Productivity and quality of vegetation grown on phosphogypsum/float rock was compared with vegetation grown on tailings treated using alternative reclamation techniques and with native vegetation on an undisturbed rangeland site. Reclamation techniques assessed included:

a) incorporation of 180 and 210 t $CaCO_3$/ha, as agricultural grade hydrated lime, with oxidized siliceous tailings,

b) 60 and 90 cm of soil cover on oxidized siliceous tailings without a contamination barrier, and

c) 35 and 50 cm of glacial till overburden cover on oxidized iron tailings with a float rock contamination barrier.

An open forest site located approximately 1 km south of the tailing ponds was selected and range productivity and quality were determined using BC Forest Service range assessment techniques (2). The site was protected from grazing by domestic animals.

Criteria for determining productivity and quality of vegetation growing on native range and acid tailings treated using phosphogypsum/float rock and other reclamation techniques were assessed between June 23 and 26, 1986. Productivity criteria, including total vegetative cover, specie cover and biomass, were assessed within 0.5 m^2 quadrats randomly located within each revegetated site. The number of quadrats varied with size of area being assessed from ten to forty-eight. Vegetative and specie cover were a visual estimate of the percentage of the ground surface covered by the vertical projection of above-ground plant parts. Biomass was the air-dried weight per unit area of above-ground plant parts.

Vegetation quality was assessed by collecting three samples of each dominant forage specie within the native range site and each revegetated site and determining the content of plant nutrients and metals in the air dried forage. Elements nitrogen, phosphorus, potassium, calcium, magnesium, iron and boron were determined by NorWest Soil Research in Langly, B.C. Zinc, lead and fluorine were determined at Cominco's analytical laboratory at Trail, B.C. Vegetation was ground in a stainless steel Wiley mill in preparation for analysis.

The growth medium within each revegetated site was sampled and properties affecting vegetative growth and quality were determined. Three samples of growth medium were taken from each site, air dried at ambient temperature in a soil drying cabinet, screened and analyzed to determine pH, salinity hazard, plant available nutrient content, particle size and available moisture storage capacity. Depth of growth medium available for root extension and moisture storage was also determined. The analyses were conducted using appropriate soil research analytical methods by NorWest Soil Research.

4. Results and Discussion

Composition, productivity and quality of vegetation were described for acid tailings revegetated using phosphogypsum/float rock, glacial till overburden/float rock, soil and a neutralizing reagent, agricultural grade hydrated lime (Tables 1,2,3). Vegetation grown on reclaimed tailings were compared with native

vegetation on range as a measure of progress toward achieving land use and productivity objectives. The potential impact of certain chemical and physical properties of the various growth media on vegetative growth and quality were discussed (Table 4).

4.1 Productivity and Quality of Vegetation on Reclaimed Acid Tailings and Native Range

4.11 Phosphogypsum/Float Rock Cover on Oxidized Iron Tailings

Nine of sixteen forage species seeded on phosphogypsum/float rock established sufficient plant populations to provide measurable vegetative cover and biomass (10). The N-fixing legume species did not establish. Mean vegetative cover for nine grass species was 9% (Table 1). Biomass production averaged 277 kg/ha. 1986 growth was sustained by maintenance fertilizer supplying the equivalent of 46 kg/ha N, 50 kg/ha K_2O and 40 kg/ha MgO (10). Grass cover and biomass production were not affected by depth of phosphogypsum covering float rock. Phosphogypsum depth averaged 35 cm and 57 cm, some 10 and 33 cm, respectively, less than planned.

Plant nutrient and metal concentrations in grasses growing on phosphogypsum ranged as follows: 0.87-2.49% N, 0.20-0.93% P, 1.40-3.39% K, 0.13-0.25% Ca, 0.10-0.26% Mg, 39-91 ppm B, 339-1180 ppm Fe, 40-90 ppm Zn, 20-65 ppm Pb and 135-460 ppm F. Fluoride concentrations increased with grass maturation to the 375-705 ppm range. The limited number of legume plants which established contained 2.07-2.48% N, 0.31-0.67% P, 3.20-5.00% K, 0.68-1.39% Ca, 0.45-0.63% Mg, 83-134 ppm B, 328-1070 ppm Fe, 65-190 ppm Zn, 25-70 ppm Pb and 250-585 ppm F. As with the grasses, fluoride concentrations in legumes increased with maturation to the 700 to 1250 ppm range.

During the stage of rapid vegetative growth, grass and legume species growing on 57 cm of phosphogypsum accumulated higher concentrations of fluoride than on the 35 cm depth (Table 3). Fluoride concentrations remained higher in matured vegetation, however, the difference was not statistically significant. Fluoride concentrations varied among forage species being lowest in grasses with highest biomass production (Table 3). Basin wildrye, thickspike wheatgrass, bluebunch wheatgrass, western wheatgrass and crested wheatgrass were the most promising forage species in terms of biomass production and fluoride content.

Limed phosphogypsum was slightly acid to very slightly alkaline, slightly saline, devoid of organic matter, low in plant available N and Mg but high in P, K, Ca and SO_4-S (Table 4). Water soluble F averaged 1488 ppm (13). Total fluoride content of phosphogypsum can be in the order of 12% (12).

In natural soils, total fluoride content is dependent on the parent material from which the soil is derived. A world wide average of 300 ppm total soil fluoride has been reported (13). In soil, soluble fluorides are approximately 0.1% of the total fluorides.

Phosphogypsum has a silt loam texture with an available water storage capacity of 0.45 cm/cm (Table 4). Depth of phosphogypsum covering float rock was relatively uniform averaging 35 cm on the shallow area with a coefficient of variability of 23% and 57 cm on the deeper area with a 13% variability coefficient. Available water storage within shallow and deep phosphogypsum averaged 16 and 26 cm respectively.

4.12 Glacial Till Overburden/Float Rock Cover on Oxidized Iron Tailings

A self-sustaining plant community dominated by drought tolerant grasses characterized vegetation growing on glacial till overburden/float rock. Vegetative cover averaged 41% but was affected by depth of overburden covering float rock (Table 1). Increasing overburden depth from 35 cm to 50 cm increased vegetative cover from 32% to 49%. Biomass production was also affected by overburden depth averaging 1276 and 1757 kg/ha, respectively, on 35 cm and 50 cm depths. Vegetation was established on the site in 1980 (6). Maintenance fertilizer has not been applied since 1984.

Plant nutrient and metal concentrations in grasses growing on glacial till overburden ranged as follows: 1.14-1.72% N, 0.15-0.32% P, 0.88-1.61% K, 0.24-0.38% Ca, 0.05-0.07% Mg, 28-43 ppm B, 463-640 ppm Fe, 75-140 ppm Zn, 25-40 ppm Pb and 5 to 85 ppm F.

Glacial till overburden was excavated from a site adjacent the iron tailings pond and was representative of material available for covering acid generating tailings. Stones reduce the volume of soil size particles to approximately 80% (Table 4). The silt loam textured soil fines were strongly acid and non-saline with a low organic matter content. Available plant nutrient levels were low for N, medium for Mg and high for P, K, Ca and S. Available water storage capacity after correcting for stone content averaged 0.30 cm/cm. Available water storage averaged 11 and 15 cm, respectively, within 35 cm and 50 cm of overburden.

4.13 Soil Cover on Oxidized Siliceous Tailings

A self-sustaining plant community dominated by the N-fixing legume alfalfa characterized vegetation growing on soil covering

oxidized siliceous tailings. Vegetative cover, legume content and biomass averaged 48%, 56% and 1598 kg/ha, respectively, on 90 cm of soil (Table 1). Vegetative cover and biomass decreased to 40% and 986 kg/ha on 60 cm of soil cover. Vegetation was established on the site in 1978 (5). Maintenance fertilizer has not been applied since 1980.

Plant nutrient and metal concentrations in alfalfa growing on soil ranged as follows: 2.24-3.67% N, 0.19-0.28% P, 2.01-2.21% K, 1.58-1.84% Ca, 0.27-0.38% Mg, 77-88 ppm B, 700-970 ppm Fe, 65-155 ppm Zn, 30-50 ppm Pb and 15-20 ppm F. Crested wheatgrass, the only grass specie growing on the site, contained 1.44-2.18% N, 0.16-0.17% P, 1.33-1.60% K, 0.26-0.29% Ca, 0.06% Mg, 29 ppm B, 441-495 ppm Fe, 30-35 ppm Zn, 20 ppm Pb and 5 ppm F.

The solum (A and B horizons) of a native range soil was used to cover oxidized siliceous tailings. Stones were numerous reducing the volume of soil size particles to approximately 60% (Table 4). The sandy loam fines were strongly acid and non-saline with a low organic matter content. Available plant nutrient levels were low for N and Mg, medium for K and high for P, Ca and S. Available water storage capacity after correcting for stone content averaged 0.19 cm/cm. Soil for several centimeters above the contact with tailings was contaminated with acid salts reducing the effective rooting depth to 52 and 75 cm, respectively, for the 60 and 90 cm soil cover depths (8). pH and electrical conductivity of soil within the contaminated zone averaged 3.8 and 5.1 ms/cm, respectively. Alfalfa and crested wheatgrass roots did not grow into the contaminated soil.

4.14 Limed Oxidized Siliceous Tailings

Oxidized siliceous tailings have a high and extremely variable lime requirement ranging from 60 to more than 200 t/ha $CaCO_3$ (8,9,10). Within the revegetated site being assessed, 180 t/ha $CaCO_3$, applied as agricultural grade hydrated lime, was required to maintain tailings pH and ECe within a range suitable for vegetation establishment throughout the entire treatment area (10). Grass dominated vegetation on limed tailings averaged 56% vegetative cover and 2230 kg/ha biomass (Table 1). Legume content was 10%. Vegetation was established on limed tailings in 1985 (9). Growth during 1986 was sustained by maintenance fertilizer supplying the equivalent of 52 kg/ha N, 64 kg/ha P_2O_5 and 40 kg/ha K_2O (10).

Plant nutrient and metal concentrations in grasses growing on oxidized siliceous tailings treated with 180 and 210 t/ha $CaCO_3$ ranged as follows: 0.98-1.98% N, 0.12-0.18% P, 1.45-2.74% K, 0.15-0.30% Ca, 0.11-0.35% Mg, 31-154 ppm B, 780-2850 ppm Fe, 25-60 ppm Zn, 40-130 ppm Pb and 5-35 ppm F. Birdsfoot trefoil, the only N-fixing legume growing on limed tailings, contained

2.53-2.78% N, 0.15-0.17% P, 2.78-3.30% K, 1.33-1.55% Ca, 0.29-0.63% Mg, 64-92 ppm B, 880-1570 ppm Fe, 50-95 ppm Zn, 40-105 ppm Pb and 10-25 ppm F.

Revegetated tailings ranged from slightly acid to neutral in reaction and were slightly saline with an extremely low organic matter content (Table 4). Available plant nutrient levels were very low for nitrogen and phosphorous, ranged from low to high for potassium and were extremely high for calcium, magnesium and sulphur. Tailings were composed primarily of sand and silt sized particles with distribution of the different size fractions being relatively uniform among sample sites. Available water storage capacity averaged 0.28 cm/cm. Effective rooting depth was limited to depth of hydrated lime incorporation (10). Grass and legume roots did not extend below the surface 15 to 25 cm. The pH of tailings within the zone occuppied by roots averaged 7.2. Immediately below the depth of root penetration tailing pH averaged 3.2. At some sites tailings below the root zone were slightly to moderately indurated.

4.15 Native Range

Native range productivity assessment was conducted on a single open forest site sustaining a diverse plant community of woody shrub and herbaceous forb and grass species. Vegetative cover and biomass production of herbaceous species averaged 60% and 2559 kg/ha, respectively, (Table 1). Vegetation was dominated by the N-fixing forb silky lupin (Lupinus sericeus) which accounted for 42% of herbaceous plant cover. Important grass species included pine grass (Calamagrotis rubescens), idaho fescue (Festca idahoensis), bluebunch wheatgrass (Agropyron spicatum) and rough fescue (Festuca scabrella).

Plant nutrient and metal concentrations in native grasses growing on the undisturbed range soil ranged as follows: 0.87-1.17% N, 0.11-0.23% P, 1.10-1.25% K, 0.17-0.25% Ca, 0.05-0.08% Mg, 5-11 ppm B, 54-140 ppm Fe, 30-40 ppm Zn, 5-15 ppm Pb and 15-30 ppm F. Silky lupin contained 2.55-2.84% N, 0.11-0.17% P, 1.37-1.58% K, 1.12-1.63% Ca, 0.26-0.34% Mg, 14-20 ppm B, 86-124 ppm Fe, 50-55 ppm Zn, 10 ppm Pb and 5-10 ppm F.

Soil development within the area was predominantly chernozemic and brunisolic on a gravelly glacio-fluvial deposit with a shallow surface (<30 cm) of fine to medium textured aeolian material. Soil parent material was derived from fine to coarse grained non-calcareous gravels. The site was gently undulating and generally well drained. Chemical and physical soil properties were assumed to be similar to the soil covering oxidized siliceous tailings.

4.2 Relative Effectiveness of Phosphogypsum/Float Rock and Alternative Techniques for Reclamation of Acid Tailings

Quantitative standards to gauge the effectiveness of phosphogypsum/float rock and alternative revegetation techniques for satisfying reclamation objectives for acid tailings at the Sullivan Concentrator are being developed. To be representative of local range productivity and quality, the assessment should be expanded to include more than one site and continued for a minimum of three growing seasons. Similarly, productivity of revegetated tailings was based on a single growing seasons vegetative growth which, in 1986, was only the first growing season following establishment for the phosphogypsum/float rock and liming techniques. The subsequent comparison of revegetated tailings productivity with that of native range must, therefore, be considered preliminary at this stage in the investigation.

The native range site was characterized by a diverse plant community dominated by a nitrogen-fixing forb and drought tolerant grasses. The vegetation reflected the semi-arid climatic conditions which prevail in the main interior valleys in southern British Columbia. At Kimberley seasonal (May-September) precipitation averaged 16 cm while evapotranspiration approximated 54 cm resulting in a seasonal climatic moisture deficit of 38 cm. Total annual precipitation averaged only 41 cm with 42% as snow. Under these conditions vegetation depends on moisture stored in the soil to sustain growth and reproduction during periods of low precipitation and high consumptive use. Depth of cover, effective rooting depth and available water storage capacity of the plant growth medium become critical factors in determining the relative effectiveness of revegetation techniques for acid tailings at the Sullivan Concentrator.

4.21 Phosphohypsum/Float Rock Cover on Oxidized Iron Tailings

Establishment, growth and quality of vegetation on phosphogypsum/float rock were less than acceptable in terms of reclamation objectives. Only nine of sixteen forage species established and forage production was equivalent to only 11% of native range productivity. Inability to establish nitrogen-fixing legumes suggests vegetation on phosphogypsum would be dominated by grass species dependent on nitrogen fertilizer to sustain normal growth and reproduction.

Forage grown on phosphogypsum was potentially toxic to grazing animals. Concentrations of fluoride in vegetation exceeded, by several times, tolerance levels for cattle, horses and sheep (15,18). During the stage of rapid vegetative growth grasses accumulated 135 to 465 ppm F (Table 3). With maturation, fluoride concentrations increased to 375 to 900 ppm. Native

grasses on range accumulated 15 to 30 ppm F. The World Health Organization suggests that chronic fluorosis may occur in grazing livestock that feed on plants with greater than 20 to 30 mg F/kg dry matter (18). The U.S. National Academy of Science suggests tolerance levels for mature cattle and horses, before indication of growth impairment, of 50 and 60 mg F/kg dry matter, respectively (15). Fluoride tolerance levels of wild ungulates deer, elk and moose are not known.

Serious doubt has been raised concerning the suitability of phosphogypsum as a plant growth medium and the feasibility of using phosphogypsum to cover acid generating tailings. Establishment and growth of forage species on the relatively shallow depth of phosphogypsum, i.e. 25-68 cm, covering float rock was poor when compared to experience on 100 cm of phosphogypsum placed on a natural soil surface. In earlier studies, legume and grass species established satisfactorily the first growing season after the experimental site was constructed in 1976 (5). Following incorporation of sufficient liming materials a mixed stand of birdsfoot trefoil and crested wheatgrass sustained satisfactory growth for eight growing seasons without maintenance fertilizer. Forage production varied with growing season averaging 1660, 701 and 1330 kg/ha when assessed in 1978, 1980 and 1982 (5,6,7). Mature crested wheatgrass and birdsfoot trefoil plants sampled in October 1984 contained 129 ppm and 465 ppm F, somewhat lower than mature plants growing on phosphogypsum/float rock in 1986 (8).

The cause of poor vegetation establishment and growth on phosphogypsum/float rock has not been identified. Several factors may have contributed to high seedling mortality during 1985 and limited vegetative growth in 1986 (9,10). The use of recently deposited phosphogypsum containing volatile and soluble fluoride compounds to construct the site, warm and dry weather for several weeks following seedling emergence and a limited depth of phosphogypsum over float rock which restricts root development, limits available water storage capacity and prevents migration of moisture upward by capillarity from below the root zone may be contributing factors. Severely limited vegetative growth may account for the extremely high levels of fluoride in vegetation.

Cultural techniques for producing forage on phosphogypsum which contain safe levels of fluoride have not been developed and alternative land use options and vegetation are being considered. Woody plants and cereal grains were assessed in preliminary field studies in 1986 (10). Survival of native shrubs wolf willow, buffaloberry, prickly rose and blue elderberry was encouraging after one growing season. In contrast the commercial forest specie lodgepole pine suffered 100% mortality. Barley, a cereal grain, established satisfactory plant populations but grain production was only 15 to 25% of production on agricultural soils. Barley leaves sampled during the stage of rapid

vegetative growth contained 240 ppm F similar to perennial grasses. Mature barley straw and grain averaged 350 ppm and 73 ppm F, respectively. Fluoride content of barley grain ranged from 40 to 115 ppm F, well below suggested tolerable concentrations for pigs and feeder lambs (<150 ppm) or chickens (<300 ppm) (15).

4.22 Glacial Till Overburden/Float Rock Cover on Oxidized Iron Tailings

Productivity of the glacial till overburden/float rock technique was affected by depth of overburden covering float rock. Crested wheatgrass and durar hard fescue forage production on overburden averaging 50 cm thick was 69% of native range forage production. On 35 cm of overburden crested wheatgrass forage production was 50% of the productivity standard. Under a semi-arid climate grasses growing on overburden/float rock would be dependent on seasonal precipitation and moisture stored in the overburden to sustain normal growth. Float rock functions as a barrier blocking root extension into the underlying tailings and upward migration of tailings moisture into the root zone, preventing use of this potential moisture source. By increasing the depth of overburden placed on float rock, the amount of pre-season precipitation retained within the growth medium available for plant growth is increased and vegetative growth will improve. With 50 cm of overburden potential moisture storage capacity was equivalent to 15 cm water, some 4 cm or 36% more than the moisture stored in 35 cm of overburden. With this reclamation technique the productivity objective might be achieved by increasing overburden depth. At present it is not known if sufficient overburden is available within a practical hauling distance to cover the tailing ponds with a thickness of 50 cm or more.

Grass vegetation produced on overburden had similar or higher concentrations of primary and secondary plant nutrients, boron and iron as native range grasses. Plant nutrient concentrations were low relative to concentrations considered adequate for normal yield (16). Plant available nitrogen in the overburden was low and vegetative growth was probably limited by a nitrogen deficiency in addition to moisture stress. Fertilizer has not been applied to the site for two years and vegetation appears to be self-sustaining. Dense grass, restricted rooting depth and competion for limited moisture prevented establishment of alfalfa, an important N-fixing legume,and woody shrubs (7).

Zinc, lead and fluoride concentrations were elevated relative to range grasses. Zinc and lead concentrations were low relative to concentrations suggested as toxic to grazing animals (17). Fluoride concentrations ranged from 5 to 85 ppm F with the majority of samples exceeding the minimum 50 ppm F suggested as

safe for cattle (15). Contamination of vegetation by phosphogypsum dust, orginating from a nearby experimental site, was suspected as the source of fluoride.

4.23 Soil Cover on Oxidized Siliceous Tailings

Productivity of alfalfa dominated vegetation growing on soil placed in direct contact with oxidized siliceous tailings was also affected by the depth of covering material. Forage production on 90 cm of soil was 62% of native range productivity. On 60 cm of soil productivity decreased to 39% of the local standard.

Placing soil directly onto tailings resulted in contamination of the growth medium for several centimeters above the tailing contact reducing the effective rooting depth to 75 cm and 52 cm, respectively, for the cover depths being compared. Soil used to cover tailings was very stoney which reduced the available water storage capacity of the root zone to 14 cm and 10 cm, respectively, for the 90 and 60 cm cover depths. As a result of contamination and excessive stoniness approximately 1.8 times as thick a cover of soil was required to provide the same available water storage capacity as was achieved with 50 cm and 35 cm of overburden covering float rock.

Alfalfa and crested wheatgrass forage contained similar to higher concentrations of primary and secondary nutrients as native range species. Relative to concentrations considered adequate for normal yield under agricultural conditions, alfalfa contained sufficient amounts of all primary, secondary and micro-nutrients whereas crested wheatgrass was deficient in N, P, K, Ca and Mg. Boron, iron, zinc and lead were elevated but not above the range considered sufficient for normal yield and well below concentrations suggested as toxic to grazing animals (16,17). Fluoride concentrations were within the range considered normal for uncontaminated soil.

4.24 Limed Oxidized Siliceous Tailings

Forage production on oxidized siliceous tailings treated with 180 t $CaCO_3$/ha and fertilized with the equivalent of 52 kg/ha N, 64 kg/ha P_2O_5 and 40 kg/ha K_2O was equivalent to 89% of production on native range. Vegetation was dominated by grasses creeping red fescue and red top and cannot be considered self-sustaining. Inspite of annual application of NPK fertilizer, the primary nutrient content of grass vegetation, while similar to native range grasses, was within the deficiency range and the plant available nutrient concentrations in the limed tailings remained low relative to levels considered adequate for normal

yield under agricultural conditions (16). Boron, iron, zinc and lead concentrations were high relative to range grasses but remained within the range considered sufficient for normal yield and well below concentrations suggested as toxic to grazing animals (16,17). Fluoride concentrations were within the range considered normal for uncontaminated soil.

Incorporation of extremely large amounts of hydrated lime was required to maintain tailings reaction and salinity within a range suitable for grass growth. However, vegetation has been growing on the site for only two years and it is not known if the quantity of lime applied was sufficient to maintain suitable growing conditions over the long term.

Grass rooting depth was limited to the depth of hydrated lime incorporation and was generally less than 25 cm. Available moisture storage capacity of the root zone was in the order of 6 cm, much less than required to sustain vegetative growth through a normal growing season. Migration of moisture from underlying acid tailings by capillarity would contribute toward reducing the root zone moisture deficit. However, acidified tailings moisture migrating into the root zone has potential to increase acidity and salinity hazard of limed tailings. Acidified tailings moisture migrating into soil covering oxidized siliceous tailings increased acidity and salinity to a degree that root growth was prevented. It is not known if limed tailings have sufficient buffering capacity to prevent a similar deterioration in growing conditions over an extended time period.

5. Conclusion

1. Development of rangeland productivity and quality standards for acid tailings reclamation at the Sullivan Concentrator has been initiated. Native range productivity and quality assessment should be expanded to include more than one open forest site and continued for a minimum of three growing seasons to be representative of local rangeland conditions.

2. Vegetation growing on phosphogypsum/float rock and alternative reclamation techniques for acid tailings did not achieve the preliminary range productivity standard during the 1986 growing season.

3. Vegetation growing on phosphogypsum/float rock accumulated fluoride-F in concentrations potentially toxic to grazing domestic livestock and wild ungulates.

4. Vegetation growing on glacial till overburden/float rock, soil covering oxidized siliceous tailings and limed oxidized siliceous tailing was of similar quality as native range forage species.

5. Phosphogypsum should not be considered an acceptable material for covering and revegetating acid generating tailings until cultural techniques have been developed which guarantee acceptable productivity of forage species safe for consumption by domestic and wild animals or until acceptable land use and revegetation alternatives have been developed. Further investigations are necessary to identify and ameliorate factors limiting vegetation establishment and growth on phosphogypsum/float rock, to limit uptake and accumulation of fluoride by plants and to assess alternative land use and revegetation options.

6. Self-sustaining vegetation has been established on glacial till overburden/float rock and soil covering oxidized siliceous tailings. Under local semi-arid climatic conditions, vegetative growth and productivity were affected by depth of growth medium and factors affecting plant available water storage capacity, moisture migration and rooting depth:

   a) available water storage capacity and forage production increased with increasing depth of overburden or soil,

   b) available water storage capacity and forage production decreased with increasing stone content of the growth medium,

   c) contamination of soil placed in direct contact with oxidized siliceous tailings reduced effective rooting depth and forage productivity, and

   d) float rock functions effectively as a barrier preventing contamination of the growth medium. With float rock rooting depth is limited to the depth of the growth medium covering float rock and migration of moisture from underlying tailings into the growth medium is blocked, preventing access by vegetation to a potential source of water.

7. Extremely large and variable quantities of hydrated lime are required to maintain oxidized siliceous tailings reaction (pH) and salinity (ECe) within a range tolerated by grasses. A rapid technique providing a reliable estimate of lime requirement has yet to be developed. Duration that current liming treatments will remain effective is unknown. Root development is limited to the depth liming materials are incorporated. Vegetation is dependent on migration of acidified moisture from the underlying non-limed tailings to sustain growth during periods of limited precipitation and high consumptive use. Migration of acidified moisture into the root zone may increase acidity and salinity to phytotoxic levels at some time in the future.

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Table 1: Comparative Productivity of Reclamation Techniques on Acid Generating Tailings at the Sullivan Concentrator

Reclamation Technique	Biomass	Vegetative Cover			Legume Content
		Total	Legume	Grass	
	(kg/ha)		(%)		(%)
1. Phosphogypsum/Float Rock Cover					
35 cm phosphogypsum	318	9	0	9	0
57 cm phosphogypsum	235	8	0	8	0
mean	277	9	0	9	0
2. Glacial Till Overburden/Float Rock Cover					
35 cm overburden	1276	32	0	32	0
50 cm overburden	1757	49	0	49	0
mean	1517	41	0	41	0
3. Soil Cover					
60 cm	986	40	21	18	53
90 cm	1598	48	27	21	56
mean	1292	44	24	20	55
4. Limed Oxidized Siliceous Tailings					
180 t $CaCO_3$/ha	2269	52	6	46	12
210 t $CaCO_3$/ha	2191	60	5	55	8
mean	2230	56	6	51	10
5. Native Range	2559	60	25	26	42

Table 2: Nutrient and Metal Content of Legume and Grass Forage Grown on Acid Generating Tailings Treated Using Alternative Reclamation Techniques

Revegetation Technique	ELEMENTAL COMPOSITION									
	N	P	K	Ca	Mg	Fe	B	Zn	Pb	F
	<-----(%)----->					<-----(ppm)----->				
1. Phosphogypsum/Float Rock Cover										
Legume	2.35	0.51	3.95	0.97	0.55	619	108	106	43	411 (1083)[1]
Grass	1.72	0.39	2.30	0.18	0.14	546	57	54	38	229 (560)
2. Glacial Till Overburden/Float Rock Cover										
Grass	1.39	0.22	1.33	0.31	0.07	536	35	99	33	56[2]
3. Soil Cover										
Legume	2.83	0.23	2.10	1.67	0.31	850	82	97	40	17
Grass	1.72	0.16	1.51	0.27	0.06	473	29	33	20	5
4. Limed Oxidized Siliceous Tailings										
Legume	2.65	0.17	3.01	1.40	0.47	846	93	67	45	18
Grass	1.69	0.14	1.65	0.26	0.18	1473	82	57	69	14
5. Native Range										
Legume	2.67	0.13	1.48	1.41	0.30	109	17	52	10	8
Grass	1.00	0.18	1.16	0.20	0.07	87	8	35	9	20

Footnote:

1. Numbers in brackets denote fluorine concentrations in matured vegetation sampled October 7, 1986.
2. Grass forage contaminated by phosphogypsum dust.

Table 1: Effect of Phosphogypsum Depth on Biomass and Fluoride-F Copntent of Legume and Grass Species

	Biomass			Fluoride-F Content					
				20.06.86			7.10.86		
Depth (cm):	35	57	$\bar{x}$	35	57	$\bar{x}$	35	57	$\bar{x}$
	(kg/ha)			(ppm)					
Legume Species									
Alfalfa	-	-	-	585	485	535	700	750	725
Birdsfoot trefoil	-	-	-	250	400	325	950	1250	1100
Cicer milkvetch	-	-	-	345	400	373	1100	1750	1425
Grass Species									
Basin wildrye	529	384	457	180	175	178	660	450	555
Thickspike wheatgrass	328	377	353	135	160	148	375	660	518
Bluebunch wheatgrass	588	196	392	225	375	300	420	530	475
Western wheatgrass	315	161	238	160	185	173	500	450	475
Creeping red fescue	320	274	297	235	200	218	675	495	585
Crested wheatgrass	319	338	329	260	200	230	585	610	598
Beardless wheatgrass	165	150	158	160	215	188	700	650	675
Altai wildrye	172	134	153	185	210	198	515	500	508
Russian wildrye	122	100	111	390	460	425	660	650	655
Big bluegrass	-	-	-	250	285	268	665	705	685
Sheep fescue	-	-	-	360	440	400	575	725	650
Durar hard fescue	-	-	-	350	465	408	900	800	850
$\bar{x}$	318	235	277	271	310	291	665	732	699
t calc.	1.29^{ns}			4.11^{xx}			0.66^{ns}	5.59^{xx}	
t.05,16df	2.12								
.05,28df	2.05								
.01,28df	2.76								

Table 4: Chemical and Physical Properties of Growth Media Within Sites Revegetated using Alternative Revegetation Techniques

	Plant Growth Medium			
	Phospho-Gypsum	Over-burden	Soil	Limed Sil Tailings
1. Chemical Properties				
pH	6.5	5.3	5.5	7.1
ECe (ms/cm)	2.6	0.5	0.6	3.1
Organic matter (%)	0.3	3.0	3.5	0.2
Plant Nutrients (ppm)				
NH_4-N	12	7	9	17
NO_3-N	5	4	5	1
P	131	119	138	3
K	476	499	293	153
Ca (ppm x 10^2)	700	14	13	240
Mg	87	104	49	385
SO_4-S	1148	53	60	567
2. Physical Properties				
Bulk density (g/cm^3)	1.04	1.24	1.35	1.20
Particle Size (%)				
<2 mm	100	80	60	100
sand	32	39	65	55
silt	62	53	30	38
clay	6	8	5	7
Moisture retention (%)				
0.1 bar	61	38	31	32
15 bar	18	8	7	9
AWSC (g/g)	.43	.30	.24	.23
AWSC (cm/cm)[1]	.45	.37	.32	.28
AWSC corr. (cm/cm)[2]	.45	.30	.19	.28
Available rooting depth (cm)	35/57	35/50	52/75	20
Available storage capacity for water (cm)	16/26	11/15	10/14	6

APPENDIX A

VARIATION IN GROWING SEASON WEATHER AT THE SULLIVAN CONCENTRATOR

Parameter		1979	1980	1981	1982	1983	1984	1985	1986	8 Year Mean	Kimb.	Cran.
Temperature °C												
Mean Monthly	May	9.7	12.0	10.8	9.5	11.7	8.4	10.5	12.6	10.7	11	-
	June	15.0	13.2	11.4	15.8	14.6	14.6	13.2	17.5	14.4	14	-
	July	18.0	16.9	15.4	15.9	15.4	20.1	19.8	15.6	17.1	18	-
	August	18.0	14.0	18.5	16.2	18.5	18.9	14.6	19.8	17.3	16	-
	Sept.	13.2	11.3	11.7	11.3	10.1	9.6	6.1	9.7	10.4	12	-
Freeze Free Period	Days	105	151	140	76	118	134	115	104	118	92	91
	Date	15 June- 28 Sept.	23 Apr.- 20 Sept.	4 May- 21 Sept.	29 May- 13 Sept.	13 May- 8 Sept.	11 May- 22 Sept.	13 May- 5 Sept.	24 May- 5 Sept.	-	-	-
Growing Degree Days		1242	1084	1083	1102	1328	1129	1044	1177	1149	1530	1550
Precipitation												
Pre-season snowfall	cm:	129	186	205	231	174	126	170	201	178	172	-
Pre-season precipitation	mm:	191	264	320	301	324	226	214	228	259	251	-
Growing season precipitation	mm:	78	207	272	186	149	163	208	194	182	163	179
Potential evapotranspiration	mm:	640	545	572	571	557	583	577	582	578	540	532
Climatic moisture deficit	mm:	562	337	300	386	408	420	369	389	396	377	353
Precipitation free period	days	23	9	13	11	16	15	16	17	15	-	-
	date	4 Sept.- 26 Sept.	23 July- 31 July.	5 Aug- 17 Aug.	15 Aug. 25 Aug.	25 July 9 Aug.	6 July 21 July	30 June 15 July	12 Aug- 28 Aug.	-	-	-

Note: 1986 weather records from Cranbrook airport.

APPENDIX B

COMPOSITION AND PRODUCTIVITY OF NATIVE RANGE AND ACID TAILINGS REVEGETATED USING ALTERNATIVE RECLAMATION TECHNIQUES

B-1

NATIVE RANGE

Transect	Mean	Standard Deviation	Coefficient of Variation
1. Vegetative Cover (%):			
1	55	11.6	21
2	59	13.8	23
3	67	15.0	22
Site	60	14.1	24
2. Biomass (kg/ha):			
1	2215	1056	48
2	2258	1028	46
3	3195	867	27
Site	2559	1069	42
3. Plant Specie Cover (%):			
Silky lupin			
1	17	11.7	69
2	23	8.7	38
3	35	12.6	36
Site	25	13.3	53
Pinegrass			
1	16	9.4	58
2	18	8.0	45
3	13	8.8	67
Site	16	8.9	55
Bluebunch wheatgrass			
1	5	3.3	65
2	3	2.4	79
3	3	2.2	72
Site	4	2.7	72
Idaho fescue			
1	5	9.2	184
2	4	10.9	286
3	8	9.6	120
Site	6	9.9	168

B-2

PHOSPHOGYPSUM/FLOAT ROCK

Plant Specie	Specie Cover			Biomass			pH			ECe		
Phosphogypsum Depth (cm):	35	57	x	35	57	x	35	57	x	35	57	x
		(%)			(kg/ha)						(ms/cm)	
1. Legumes												
Alfalfa	0	0	0	0	0	0	6.9	6.8	6.9	2.3	2.9	2.6
Birdsfoot trefoil	0	0	0	0	0	0	7.3	6.4	6.9	2.5	2.4	2.5
Sainfoin	0	0	0	0	0	0	7.2	5.1	6.2	2.7	2.9	2.8
Cicer milkvetch	0	0	0	0	0	0	4.9	6.7	5.8	3.1	2.8	3.0
2. Grasses												
Big bluegrass	0	0	0	0	0	0	6.5	7.1	6.8	3.9	2.3	3.1
Crested wheatgrass	8	10	9	319	338	330	6.5	6.7	6.6	3.6	4.2	3.9
Thickspike wheatgrass	13	13	13	328	377	353	6.2	6.7	6.5	2.8	2.8	2.8
Western wheatgrass	12	9	10	315	161	238	6.8	6.8	6.8	2.1	2.3	2.2
Beardless wheatgrass	5	5	5	165	150	158	6.4	7.0	6.7	2.0	2.0	2.0
Bluebunch wheatgrass	10	5	7	588	196	392	7.2	6.3	6.8	2.9	3.3	3.1
Hard. fescue	0	0	0	0	0	0	6.8	6.3	6.6	2.2	2.1	2.2
Creeping red fescue	9	7	8	320	274	297	6.7	5.4	6.1	2.5	2.6	2.6
Sheep fescue	0	0	0	0	0	0	6.3	6.7	6.5	2.6	2.2	2.4
Russian wildrye	9	8	8	122	100	111	5.7	6.2	6.0	2.0	2.2	2.1
Altai wildrye	6	4	5	172	134	153	5.6	7.0	6.3	2.1	1.8	2.0
Basin wildrye	13	9	11	529	384	457	6.9	6.7	6.8	2.6	2.0	2.3
X	9.4	7.7		318	235		6.5	6.5		2.6	2.6	
t calc.	1.26ns			1.29ns			ns			ns		

GLACIAL TILL OVERBURDEN/FLOAT ROCK

Sample Site	Overburden Depth		Vegetative Cover		Biomass		Specie Cover		
	M1	M2	M1	M2	M1	M2	Crested Wheatgrass Fairway	Crested Wheatgrass Nordan	Hard Fescue
	(cm)		(%)		(kg/ha)			(%)	
1	-	-	22	44	720	1156	22	0	44
2	30	-	25	40	1300	1226	25	5	35
3	34	27	21	50	1140	1406	21	8	42
4	36	43	26	40	1292	1446	26	10	30
5	41	44	28	39	1156	2200	28	24	15
6	31	34	32	55	1290	2046	32	45	10
7	33	-	24	75	1456	1880	24	25	50
8	35	48	34	39	962	1700	34	34	0
9	-	51	36	36	1022	2002	34	31	5
10	41	47	28	55	1016	1140	28	0	55
11	30	41	40	52	2236	1376	40	10	40
12	35	-	28	38	1044	1570	25	28	10
13	-	47	36	40	1126	2036	36	37	3
14	40	58	42	35	1754	1956	42	23	10
15	38	62	41	45	1796	1938	41	40	5
16	29	37	39	65	1070	1144	39	10	55
17	33	71	33	38	1660	2066	33	38	0
18	-	70	44	75	1280	2442	44	55	20
19	37	62	30	70	1066	2980	27	45	25
20	38	47	34	43	1124	1420	34	38	0
X	35	49	32	49	1276	1757	32	25	23
S	3.9	12.5	7.1	13.1	352	486	7.0	16.4	19.6
CV (%)	11	25	22	27	28	28	22	66	85
t calc.	4.49		4.41		3.23				

Note:

1. Value of "t" for 15df, .10, .05, .01 probability 1.75, 2.13, 2.95
   Value of "t" for 19df, .10, .05, .01 probability 1.73, 2.09, 2.86

SOIL COVERING OXIDIZED SILICEOUS TAILINGS

Quadrat	Depth (cm):	Vegetative Cover		Biomass		Alfalfa		Crested wheatgrass	
		60	90	60	90	60	90	60	90
		(%)		(kg/ha)		(%)		(%)	
1		40	55	1380	1686	25	45	10	10
2		38	65	1144	2196	20	35	18	39
3		30	50	926	1660	15	35	15	15
4		25	45	682	2208	12	30	13	15
5		40	40	622	1224	15	20	15	20
6		55	45	924	1242	20	18	35	27
7		38	40	866	1320	18	20	20	20
8		40	50	1160	1580	25	25	15	25
9		45	40	1020	1446	30	15	15	25
10		45	45	1140	1420	25	25	20	20
X		40	48	986	1598	21	27	18	21
S		8.2	7.9	231	356	5.7	9.4	6.8	6.2
CV (%)		21	16	23	22	27	35	38	29
t calc.		2.09		6.90		1.45ns		0.93ns	

Note:

1. Value of "t" for 9df .10, .05, .01 probability 1.83, 2.26 and 3.25.

LIMED OXIDIZED SILICEOUS TAILINGS

t/ha $CaCO_3$:	60		90		120		150		180		210	
Parameter:	South	North	South	North	South	North	South	North	South	North	South	North
No. samples	5	5	5	5	5	5	5	5	5	5	5	5
Vegetative Cover (%):												
X	45	0	50	0	42	9	54	16	78	25	59	60
S	20	-	30	-	44	20	36	7	8	7	23	23
CV (%)	45	-	60	-	105	224	66	41	11	28	39	39
Range	25-70	0	0-80	0	0-90	0-45	18-100	11-23	65-85	15-32	40-95	30-80
Frequency	100	0	80	0	60	20	100	100	100	100	100	100
Biomass (kg/ha):												
X	920	0	1456	0	890	191	2670	450	2348	2189	2232	2149
S	467	-	981	-	1012	428	1478	228	807	1019	919	951
CV (%)	51	-	67	-	114	224	55	51	34	47	41	44
Range	320-1560	0	0-2624	0	0-2006	0-956	620-4540	202-658	1450-3240	770-3366	1400-3504	1086-3038
Specie Cover (%):												
Birdsfoot Trefoil												
X	0	0	<1	0	1	0	9	0	8	3	7	3
Range	0	-	0-2	-	0-5	-	2-25	-	0-15	0-5	5-15	0-5
Frequency (%)	0	0	20	0	20	0	100	0	80	80	100	80
Fescue												
X	42	0	50	0	37	8	19	7	48	18	22	27
Range	20-60	-	0-78	-	0-85	0-40	0-50	2-13	45-55	0-30	10-43	15-40
Frequency (%)	100	0	80	0	60	20	80	100	100	80	100	100
Red Top												
X	3	0	0	0	4	1	16	8	0	3	30	30
Range	0-10	-	-	-	0-15	0-5	0-30	3-13	-	0-15	20-45	15-45
Frequency (%)	40	0	0	0	40	20	80	100	0	20	100	100

APPENDIX C

NUTRIENT AND METAL CONTENT OF FORAGE SPECIES GROWING ON NATIVE RANGE AND ACID TAILINGS REVEGETATED USING ALTERNATIVE RECLAMATION TECHNIQUES

NATIVE RANGE

Plant Specie	TOTAL ELEMENT CONCENTRATION									
	N	P	K	Ca	Mg	B	Fe	Zn	Pb	F
	<-----(%)----->					<-----(ppm)----->				
Silky lupin										
1	2.55	0.17	1.58	1.12	0.26	20	86	50	10	10
2	2.61	0.12	1.37	1.63	0.34	14	118	55	10	10
3	2.84	0.11	1.50	1.47	0.29	17	124	50	10	5
X	2.67	0.13	1.48	1.41	0.30	17	109	52	10	8
Idaho fescue										
1	1.11	0.19	1.10	0.21	0.08	11	140	40	15	20
2	1.17	0.21	1.14	0.25	0.08	8	97	35	10	20
3	0.89	0.17	1.15	0.17	0.05	5	102	35	5	15
X	1.06	0.19	1.13	0.21	0.07	8	113	36	10	18
Bluebunch wheatgrass										
1	0.87	0.11	1.14	0.17	0.06	5	59	35	5	30
2	0.99	0.15	1.25	0.19	0.07	8	70	35	10	20
3	0.92	0.23	1.16	0.17	0.06	10	54	30	5	15
X	0.93	0.16	1.18	0.18	0.06	8	61	33	7	22

PHOSPHOGYPSUM/FLOAT ROCK

Forage Specie	Gypsum Depth	TOTAL ELEMENT CONCENTRATION									F	
		N	P	K	Ca	Mg	B	Fe	Zn	Pb	24.07.86	10.10.86
	(cm)	<-----(%)----->					<-----(ppm)----->				(ppm)	
Alfalfa	35	2.37	0.40	3.20	1.10	0.59	134	1070	145	70	585	700
	56	2.46	0.53	3.35	0.85	0.45	112	700	65	40	485	750
	X	2.42	0.47	3.28	0.98	0.52	123	885	105	55	535	725
Birdsfoot trefoil	35	2.14	0.50	4.00	0.71	0.53	105	328	100	40	250	950
	56	2.58	0.64	4.40	1.05	0.55	126	760	70	25	400	1250
	X	2.36	0.57	4.20	0.88	0.54	116	544	85	33	325	1100
Cicer milkvetch	35	2.07	0.67	5.00	1.39	0.63	86	446	190	40	345	1100
	56	2.48	0.31	3.75	0.68	0.52	83	409	65	40	400	1750
	X	2.28	0.49	4.38	1.04	0.58	85	428	128	40	373	1425
Big bluegrass	35	1.69	0.20	1.58	0.24	0.14	91	1180	90	65	250	665
	56	2.20	0.26	1.54	0.19	0.14	82	720	85	60	285	705
	X	1.95	0.23	1.56	0.22	0.14	87	950	88	63	268	685
Crested wheatgrass	35	1.40	0.32	1.57	0.19	0.13	59	575	70	45	260	585
	56	1.49	0.30	1.45	0.14	0.10	39	339	45	25	200	610
	X	1.45	0.31	1.51	0.17	0.12	49	457	58	35	230	598
Thickspike wheatgrass	35	1.38	0.24	1.80	0.16	0.12	46	510	65	55	135	375
	56	0.87	0.36	1.59	0.13	0.10	55	610	40	35	160	660
	X	1.13	0.30	1.70	0.15	0.11	51	560	53	45	148	518
Western wheatgrass	35	1.75	0.33	2.02	0.13	0.14	48	446	55	30	160	500
	56	2.13	0.42	2.35	0.16	0.14	56	441	40	20	185	450
	X	1.94	0.38	2.19	0.15	0.14	52	444	48	25	173	475
Beardless wheatgrass	35	2.14	0.28	1.79	0.19	0.11	44	457	55	35	160	700
	56	2.04	0.28	1.59	0.25	0.10	73	698	50	40	215	650
	X	2.09	0.28	1.69	0.22	0.11	59	578	53	38	188	675
Bluebunch wheatgrass	35	1.54	0.23	1.40	0.21	0.12	66	690	55	40	225	420
	56	1.51	0.33	1.45	0.15	0.10	60	436	50	40	375	530
	X	1.53	0.28	1.43	0.18	0.11	63	563	53	40	300	475

C-2 - Cont'd

Forage Specie	Gypsum Depth	TOTAL ELEMENT COMPOSITION									F	
		N	P	K	Ca	Mg	B	Fe	Zn	Pb	24.07.86	10.10.86
	(cm)	(%)					(ppm)				(ppm)	
Hard fescue	35	2.04	0.28	2.00	0.28	0.15	75	640	70	65	350	900
	56	1.76	0.33	2.01	0.28	0.15	79	560	50	45	465	800
	X	1.90	0.31	2.01	0.28	0.15	77	600	60	55	408	850
Creeping red fescue	35	1.52	0.33	1.80	0.14	0.12	61	565	55	50	235	675
	56	1.43	0.27	1.90	0.18	0.14	73	790	50	45	200	495
	X	1.48	0.30	1.85	0.16	0.13	67	678	53	48	218	585
Sheep fescue	35	1.97	0.27	2.02	0.29	0.16	82	765	75	60	360	575
	56	2.46	0.35	2.15	0.23	0.18	91	550	60	45	440	725
	X	2.22	0.31	2.09	0.26	0.17	87	658	68	53	400	650
Russian wildrye	35	2.03	0.54	3.15	0.23	0.26	64	463	60	45	390	660
	56	2.49	0.93	3.39	0.20	0.23	69	350	45	30	460	650
	X	2.27	0.74	3.27	0.22	0.25	67	407	53	38	425	655
Altai wildrye	35	1.51	0.49	3.05	0.19	0.15	40	505	55	30	185	515
	56	2.33	0.51	2.70	0.22	0.15	42	473	45	30	210	500
	X	1.92	0.50	2.88	0.21	0.15	41	489	50	30	198	508
Basin wildrye	35	1.53	0.39	2.00	0.18	0.13	68	770	70	50	180	660
	56	1.81	0.39	2.20	0.13	0.14	64	710	65	40	175	450
	X	1.67	0.39	2.10	0.16	0.14	66	740	68	45	178	555
Cheatgrass		1.14	0.21	0.46	0.32	0.18	20	1120	165	90	440	
Aspen (leaves)		2.29	0.32	1.91	0.69	0.42	90	705	140	75	330	
Native Plants on Undisturbed Soil												
Aspen		2.59	0.44	1.78	0.99	0.23	40	495	195	55	35	
Idaho fescue		1.06	0.19	1.13	0.21	0.07	8	113	36	10	18	
Bluebunch wheatgrass		0.93	0.16	1.18	0.18	0.06	8	61	33	7	22	
Silky lupin		2.67	0.13	1.48	1.41	0.30	17	109	52	10	8	

GLACIAL TILL OVERBURDEN/FLOAT ROCK

Plant Specie	TOTAL ELEMENT CONCENTRATION									
	N	P	K	Ca	Mg	B	Fe	Zn	Pb	F
	<-----(%)----->					<-----(ppm)----->				
Crested Wheatgrass var. Fairway										
1	1.60	0.18	1.46	0.25	0.06	39	620	120	30	35
2	1.40	0.18	1.44	0.29	0.05	38	560	140	25	25
3	1.50	0.17	1.43	0.33	0.05	36	560	135	35	45
X	1.50	0.18	1.44	0.29	0.05	38	580	132	30	35
Crested Wheatgrass var. Nordan										
1	1.72	0.26	1.46	0.38	0.07	29	484	95	30	65
2	1.60	0.16	0.88	0.38	0.07	28	500	135	25	5
3	1.54	0.32	1.15	0.34	0.07	35	565	110	30	60
X	1.62	0.25	1.16	0.37	0.07	31	516	113	28	43
Durar hard fescue										
1	1.14	0.18	1.61	0.25	0.07	38	565	90	40	55
2	1.18	0.20	1.44	0.25	0.06	43	640	90	40	65
3	1.17	0.15	1.43	0.24	0.07	32	463	75	35	85
X	1.16	0.18	1.49	0.25	0.07	38	556	85	38	68
Native Plants on Undisturbed Soils										
Idaho fescue	1.06	0.19	1.13	0.21	0.07	8	113	36	10	18
Bluebunch wheatgrass	0.93	0.16	1.18	0.18	0.06	8	61	33	7	22
Silky lupin	2.67	0.13	1.48	1.41	0.30	17	109	52	10	8

SOIL COVERING OXIDIZED SILICEOUS TAILINGS

Plant Specie	TOTAL ELEMENT CONCENTRATION									
	N	P	K	Ca	Mg	B	Fe	Zn	Pb	F
	<-----(%)----->					<-----(ppm)----->				
Created wheatgrass										
1	2.18	0.16	1.60	0.29	0.06	29	441	35	20	5
2	1.54	0.16	1.33	0.27	0.06	29	484	30	20	5
3	1.44	0.17	1.59	0.26	0.06	28	495	35	20	5
X	1.72	0.16	1.51	0.27	0.06	29	473	33	20	5
Alfalfa var. rambler										
1	3.67	0.22	2.08	1.84	0.38	88	970	155	50	15
2	2.59	0.28	2.01	1.59	0.27	81	880	70	40	15
3	2.24	0.19	2.21	1.58	0.29	77	700	65	30	20
X	2.83	0.23	2.10	1.67	0.31	82	850	97	40	17
Native Plants on Undisturbed Soil										
Idaho fescue	1.06	0.19	1.13	0.21	0.07	8	113	36	10	18
Bluebunch wheatgrass	0.93	0.16	1.18	0.18	0.06	8	61	33	7	22
Silky lupin	2.67	0.13	1.48	1.41	0.30	17	109	52	10	8

LIMED OXIDIZED SILICEOUS TAILINGS

$CaCO_3$ Rate	TOTAL ELEMENT CONCENTRATION									
	N	P	K	Ca	Mg	B	Fe	Zn	Pb	P
(kg/ha)	<-----(%)----->					<-----(ppm)----->				
1. Durar hard fescue[1]										
60	1.61	0.10	1.84	0.29	0.09	79	1527	70	82	22
90	1.41	0.13	1.52	0.29	0.10	59	957	48	50	18
120	1.74	0.13	1.76	0.28	0.15	68	1183	62	52	17
X	1.59	0.12	1.71	0.29	0.11	69	1222	60	61	19
2. Creeping red fescue										
150	1.96	0.17	1.69	0.19	0.19	111	2303	73	103	25
180	1.58	0.14	2.12	0.25	0.15	94	1888	48	107	23
210	1.64	0.14	1.53	0.24	0.20	95	1763	52	85	10
X	1.73	0.15	1.78	0.23	0.18	100	1985	58	98	19
3. Red Top										
150	1.57	0.16	2.26	0.22	0.26	74	1429	53	68	13
180	1.07	0.14	2.28	0.22	0.24	67	1077	30	55	30
210	1.26	0.16	2.35	0.21	0.25	77	1287	37	43	12
X	1.30	0.15	2.30	0.22	0.25	73	1264	40	55	18
4. Birdsfoot trefoil										
150	2.71	0.17	2.95	1.46	0.44	90	1623	97	80	20
180	2.65	0.16	3.06	1.44	0.41	70	1220	65	82	20
210	2.65	0.17	3.01	1.40	0.47	83	846	67	45	18
X	2.67	0.17	3.01	1.43	0.44	81	1230	76	69	19
5. Native Plants on Undisturbed Soil										
Idaho fescue	1.06	0.19	1.13	0.21	0.07	8	113	36	10	18
Bluebunch wheatgrass	0.93	0.16	1.18	0.18	0.06	8	61	33	7	22
Silky lupin	2.67	0.13	1.48	1.41	0.30	17	109	52	10	8

Note: 1 Values presented are means of three composite samples.

APPENDIX D

PHYSICAL AND CHEMICAL PROPERTIES OF PLANT GROWTH MEDIA FOR ALTERNATIVE RECLAMATION TECHNIQUES

D-1

PHOSPHOGYPSUM

Phosphogypsum depth (cm):	35			57			
	1	2	3	1	2	3	x
Bulk density (g/cm^3):	1.02	1.13	1.08	1.01	1.02	0.98	1.04
Particle size distribution:							
% sand	38	28	30	32	30	34	32
% silt	55	65	65	62	64	61	62
% clay	7	7	5	6	6	5	6
Moisture retention (%):							
0.1 bar	61.6	63.3	58.1	63.0	61.1	58.5	60.9
15 bar	17.5	20.2	17.0	16.6	17.9	21.0	18.4
AWSC	44.1	43.1	41.1	46.4	43.2	37.5	42.5
Field moisture (%)	17.2	17.7	19.5	23.9	19.4	23.4	20.1
pH	7.2	7.4	6.9	6.0	6.9	6.0	6.7
ECe (ms/cm)	3.8	3.8	4.0	4.4	4.0	5.1	4.2
Organic matter (%)	0.5	0.4	0.2	0.3	0.2	0.2	0.3
Plant nutrients (ppm):							
NH_4-N	3	4	8	24	10	24	12
NO_3-N	2	6	8	7	2	4	5
P	121	122	137	140	125	140	131
K	504	453	335	558	309	699	476
Ca ($X10^3$ppm)	72	70	70	70	70	70	70
Mg	59	96	51	105	28	182	87
SO_4-S	1030	1130	1040	1240	1030	1420	1148

D-2

GLACIAL TILL OVERBURDEN/FLOAT ROCK

Soil Property	Sample Site 1	2	3	x
Bulk density (g/cm^3)	1.38	1.07	1.26	1.24
Particle size distribution:				
% sand	40	38	38	39
% silt	51	55	53	53
% clay	9	7	9	8
Moisture retention (%):				
0.1 bar	33.4	40.9	39.3	37.9
15 bar	6.8	8.3	8.5	7.9
AWSC	26.6	32.6	30.8	30.0
Field moisture content	8.3	11.7	10.7	10.2
pH	5.1	5.3	5.4	5.3
ECe (ms/cm)	0.6	0.5	0.3	0.5
Organic matter (%)	3.0	3.5	2.5	3.0
Plant nutrients (ppm)				
NH_4-N	8	7	5	7
NO_3-N	5	3	3	4
P	114	121	122	119
K	474	525	498	499
Ca	1452	1743	1137	1444
Mg	113	119	80	104
SO_4-S	71	59	29	53

D-3

SOIL COVERING OXIDIZED SILICEOUS TAILINGS

Soil Property	Sample Site 1	2	3	x
Particle size distribution:				
% sand	64	66	64	65
% silt	31	29	31	30
% clay	5	5	5	5
Moisture retention (%):				
0.1 bar	29.4	31.3	30.8	30.5
15 bar	7.5	7.1	7.7	7.4
AWSC	21.9	24.2	23.1	23.0
pH	5.4	5.5	5.5	5.5
ECe (ms/cm)	1.2	0.4	0.2	0.6
Organic matter (%)	3.2	3.5	3.9	3.5
Plant nutrients (ppm)				
NH_4-N	12	9	7	9
NO_3-N	9	4	1	5
P	121	160	133	138
K	306	291	282	293
Ca	1452	1161	1137	1250
Mg	42	53	52	49
SO_4-S	97	41	41	60

D-4

LIMED OXIDIZED SILICEOUS TAILINGS

Properties	Sample Sites: t/ha. $CaCO_3$: 60 N	60 S	90 N	90 S	120 N	120 S	x
Bulk density (g/cm^3)	1.23	1.25	1.33	1.06	1.20	1.12	1.20
Particle size distribution:							
% sand	48	60	54	58	58	52	55
% silt	47	31	38	35	35	39	38
% clay	5	9	8	7	7	9	7
Moisture retention (%):							
0.1 bar	36.9	26.0	38.7	26.0	34.1	29.1	31.8
15 bar	8.5	7.7	10.5	7.4	8.8	10.0	8.8
AWSC	28.4	18.3	28.2	18.6	25.3	19.1	23.0
Field Moisture (%)	21.4	16.2	19.7	18.6	23.4	11.9	18.5
pH	2.8	2.6	2.4	2.8	2.5	2.7	2.6
ECe (ms/cm)	6.4	7.6	7.8	10.0	6.7	7.8	7.7
Organic matter (%)	0.2	0.1	0.4	0.1	0.2	0.1	0.2
Plant nutrients (ppm):							
NH_4-N	53	5	21	7	7	7	17
NO_3-N	1	1	1	1	1	1	1
P	4	4	4	3	2	2	3
K	137	243	155	131	119	131	153
Ca	13665	21000	28500	18300	28800	33750	24003
Mg	210	428	210	770	156	534	385
SO_4-S	1570	395	380	556	70	432	567

APPENDIX E

pH AND ECe OF OXIDIZED SILICEOUS TAILINGS TREATED WITH VARYING AMOUNTS OF HYDRATED LIME

t/ha $CaCO_3$:	60		90		120		150		180		210	
Sample Site	South	North	South	North	South	North	South	North	South	North	South	North
1. Tailings pH:												
1	3.3	2.6	6.6	2.7	6.1	2.8	6.6	3.9	7.4	6.9	7.5	5.9
2	7.2	2.2	6.8	2.6	6.7	3.0	7.0	2.2	7.4	7.2	7.5	7.7
3	3.7	2.5	5.0	2.8	2.5	2.8	7.4	2.5	7.5	5.6	7.2	7.4
4	7.1	2.7	4.8	3.0	3.2	2.8	3.1	-	7.5	7.1	7.1	7.4
5	7.3	2.7	3.0	2.7	3.2	3.3	2.2	7.1	7.4	7.3	6.2	7.5
X	5.7	2.5	5.2	2.8	4.3	2.9	5.3	3.9	7.4	6.8	7.1	7.2
S	2.0	0.2	1.5	0.2	1.9	0.2	2.4	2.2	0.1	0.7	0.5	0.7
CV (%)	36	8	30	6	44	8	46	57	1	10	8	10
2. Tailings ECe (ms/cm):												
1	5.1	9.9	3.0	8.0	1.5	6.2	2.0	10.0	2.3	2.0	2.4	5.4
2	3.7	11.5	1.8	8.2	1.7	13.0	1.9	8.4	2.1	1.9	2.4	4.8
3	3.0	10.1	1.9	13.2	6.1	15.0	1.5	10.8	2.0	5.6	2.3	2.7
4	3.1	14.8	1.2	13.0	4.6	13.2	2.5	-	2.0	3.1	2.1	2.4
5	1.8	7.2	9.0	15.0	4.4	7.0	6.6	7.4	1.9	1.5	2.4	10.0
X	3.3	10.7	3.4	11.5	3.7	10.9	2.9	9.2	2.1	2.8	2.3	5.1
S	1.2	2.8	3.2	3.2	2.0	4.0	2.1	1.5	0.2	1.7	0.1	3.1
CV (%)	36	26	94	28	54	37	72	17	7	59	6	60

Note:

1. Hydrated lime applied August 1980 for treatments 60, 90 and 120 t/ha $CaCO_3$.
2. Hydrated lime applied August 1980 (60, 90, 120 t/ha) and June 1984 (90 t/ha) for treatments 150, 180 and 210 t/ha $CaCO_3$.